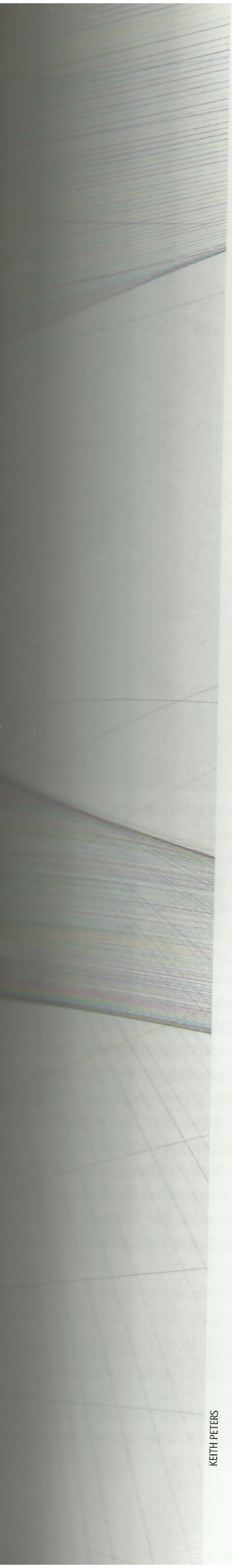


KEITH PETERS

Craig Callender is a philosophy professor at the University of California, San Diego. He wrote the graphic text *Introducing Time* and is working on a book on the philosophy, physics and cognitive science of time entitled *Time: From the Inside Out*. He assures us that his lifelong interest in time has nothing to do with his last name.

PHYSICS

IS TIME AN ILLUSION?

The concepts of time and change may emerge from a universe that, at root, is utterly static

By Craig Callender

As you read this sentence, you probably think that this moment—right now—is what is happening. The present moment feels special. It is real. However much you may remember the past or anticipate the future, you live in the present. Of course, the moment during which you read that sentence is no longer happening. This one is. In other words, it feels as though time flows, in the sense that the present is constantly updating itself. We have a deep intuition that the future is open until it becomes present and that the past is fixed. As time flows, this structure of fixed past, immediate present and open future gets carried forward in time. This structure is built into our language, thought and behavior. How we live our lives hangs on it.

Yet as natural as this way of thinking is, you will not find it reflected in science. The equations of physics do not tell us which events are occurring right now—they are like a map without the "you are here" symbol. The present moment does not exist in them, and therefore neither does the flow of time. Additionally, Albert Einstein's theories of relativity suggest not only that there is no single special present but also that all moments are equally real [see "That Mysterious Flow," by Paul Davies, on page 8]. Fundamentally, the future is no more open than the past.

The gap between the scientific understanding of time and our everyday understanding of time has troubled thinkers throughout history. It has widened as physicists have gradually stripped time of most of the attributes we commonly ascribe to it. Now the rift between the time of physics and the time of experience is reaching its logical conclusion, for many in theoretical physics have come to believe that time fundamentally does not even exist.

WITHOUT THINKING DEEPLY ABOUT TIME, PHYSICISTS MAY NEVER MAKE PROGRESS ON A UNIFIED THEORY.

The idea of a timeless reality is initially so startling that it is hard to see how it could be coherent. Everything we do, we do in time. The world is a series of events strung together by time. Anyone can see that my hair is graying, that objects move, and so on. We see change, and change is the variation of properties with respect to time. Without time, the world would be completely still. A timeless theory faces the challenge of explaining how we see change if the world is not really changing.

Recent research attempts to perform just this feat. Although time may not exist at a fundamental level, it may arise at higher levels—just as a table feels solid even though it is a swarm of particles composed mostly of empty space. Solidity is a collective, or emergent, property of the particles. Time, too, could be an emergent property of whatever the basic ingredients of the world are.

This concept of emergent time is potentially as revolutionary as the development of the theories of relativity and of quantum mechanics a century ago. Einstein said that the key step forward in developing relativity was his reconceptualization of time. As physicists pursue his dream of unifying relativity with quantum mechanics, they believe that time is again central. In 2008 the Foundational Questions Institute (FQXi) sponsored an essay contest on the nature of time, and a veritable who's who of modern physics weighed in. Many held that a unified theory will describe a timeless world. Others were loath to get rid of time. The one thing they agreed on was that without thinking deeply about time, progress on unification may well be impossible.

THE RISE AND FALL OF TIME

OUR RICH COMMONSENSICAL notions of time have suffered a withering series of demotions throughout the ages. Time has many jobs to do in physics, but as physics has progressed, these jobs have been outsourced one by one.

It may not be obvious at first, but Isaac Newton's laws of motion require time to have many specific features. All observers in principle agree on the sequence in which events happen. No matter when or where an event occurs, classical physics assumes that you can objectively say whether it happens before, after or simultaneously with any other event in the universe. Time therefore provides a complete ordering of all the events in the world. Simultaneity is absolute—an observer-independent fact. Furthermore, time must be continuous so that we can define velocity and acceleration.

Classical time must also have a notion of duration—what physicists call a metric—so that we can tell how far apart in time events are from one another. To say that Olympic sprinter Usain Bolt can run as fast as 27 miles per hour, we need to have a measure of what an hour is. Like the order of events, duration is observer-independent. If Alice and Bob leave school at 3 P.M., go their separate ways, and then meet back at home at 6 P.M., the amount of time that has elapsed for Alice is equal to the amount of time that has elapsed for Bob.

In essence, Newton proposed that the world comes equipped with a master clock. The clock uniquely and objectively carves the world up into instants of time. Newton's physics listens to the ticking of this clock and no other. Newton additionally felt that time flows and that this flow gives us an arrow telling us which direction is the future, although these extra features are not strictly demanded by his laws.

Newton's time may seem old hat to us now, but a moment's reflection reveals how astonishing it is. Its many features—order, continuity, duration, simultaneity, flow and the arrow—are logically detachable, yet they all stick together in the master clock that Newton dubbed "time." This assembly of features succeeded so well that it survived unscathed for almost two centuries.

Then came the assaults of the late 19th and early 20th centuries. The first was the work of Austrian physicist Ludwig Boltzmann, who reasoned that, because Newton's laws work equally well going forward or backward in time, time has no built-in arrow. Instead he proposed that the distinction between past and future is not intrinsic to time but arises from asymmetries in how the matter in the universe is organized. Although physicists still debate the details of this proposal, Boltzmann convincingly plucked away one feature of Newtonian time.

Einstein mounted the next assault by doing away with the idea of absolute simultaneity. According to his special the-

IN BRIEF

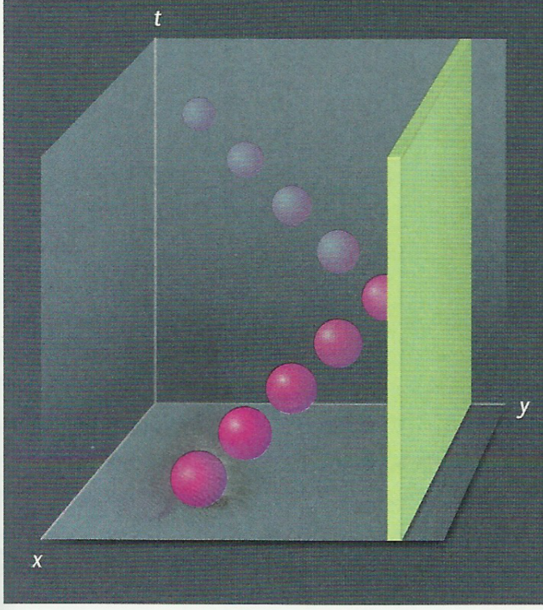
Time is an especially hot topic right now in physics. The search for a unified theory is forcing physicists to reexamine very basic assumptions, and few things are more basic than time.

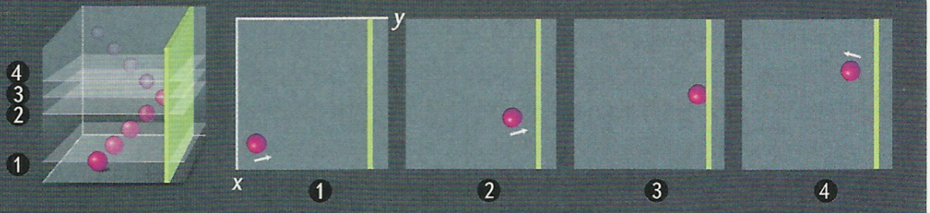
Some physicists argue that there is no such thing as time. Others think time ought to be promoted rather than demoted. In between these two positions is the fascinating idea that time exists but is not fundamental. A static world somehow gives rise to the time we perceive.

Philosophers have debated such ideas since before the time of Socrates, but physicists are now making them concrete. According to one, time may arise from the way that the universe is partitioned; what we perceive as time reflects the relations among its pieces.

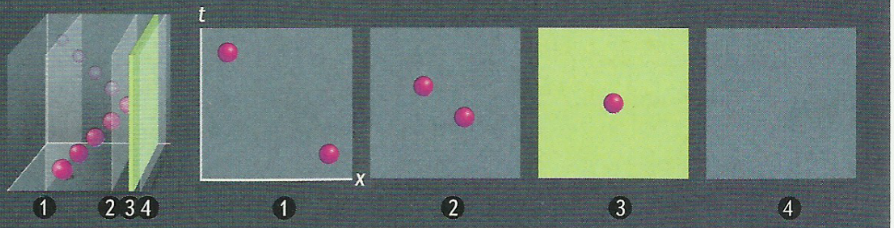
How Time Is Not Like Space

Physicists, artists and graph makers of all kinds routinely depict time as another dimension of space, creating a unified spacetime—shown here as a three-dimensional block in which a ball bounces off a wall. Relativity theory holds that spacetime can be sliced up in various ways. But not all are equally sensible.





The usual way takes slices of space at successive moments of time, creating a movie of the ball's motion. Each frame leads to the next, according to the familiar laws of physics.



An alternative considers slices not from past to future but from left to right. Each slice is part space, part time. To the left of the wall, the ball appears in two positions; on the right, it does not appear at all. If this slicing seems strange, it should: it makes the laws of physics very unwieldy.

ory of relativity, what events are happening at the same time depends on how fast you are going. The true arena of events is not time or space, but their union: spacetime. Two observers moving at different velocities disagree on when and where an event occurs, but they agree on its spacetime location. Space and time are secondary concepts that, as mathematician Hermann Minkowski, who had been one of Einstein's university professors, famously declared, "are doomed to fade away into mere shadows."

Things only get worse in 1915 with Einstein's general theory of relativity, which extends special relativity to situations where the force of gravity operates. Gravity distorts time, so that a second's passage here may not mean the same thing as a second's passage there. Only in rare cases is it possible to synchronize clocks and have them stay synchronized, even in principle. You cannot generally think of the world as unfolding, tick by tick, according to a single time parameter. In extreme situations, the world might not be carvable into instants of time at all. It then becomes impossible to say that an event happened before or after another.

General relativity contains many functions with the English word "time" attached to them: coordinate time, proper time, global time. Together they perform many of the jobs Newton's single time did, but individually none of them seems worthy of the title. Either the physics does not listen to these clocks, or, if it does, those clocks apply only to small patches of the universe or to particular observers. Although physicists today fret that a unified theory will have to eliminate time, a good argument can be made that time was already lost by 1915 and that we just have not fully come to grips with it yet.

TIME AS THE GREAT STORYTELLER

WHAT GOOD IS TIME, THEN? You might be tempted to think that the difference between space and time has nearly vanished and that the true arena of events in a relativistic universe is a big four-dimensional block. Relativity appears to spatialize time: to turn it into merely one more direction within the block. Spacetime is like a loaf of bread that you can slice in different ways, called either "space" or "time" almost arbitrarily.

Yet even in general relativity, time retains a distinct and important function: namely, that of locally distinguishing between "timelike" and "spacelike" directions. Timelike-related events are those that can be causally related. An object or signal can pass from one event to the other, influencing what happens. Spacelike-related events are causally unrelated. No object or signal can get from one to the other. Mathematically, a mere minus sign differentiates the two directions, yet this minus sign has huge effects. Observers disagree on the sequence of spacelike events, but they all agree on the order of timelike events. If one observer perceives that an event can cause another, all observers do.

TIME MAY BE A CONVENIENT FICTION THAT NO MORE EXISTS IN THE NATURAL WORLD THAN MONEY DOES.

In my own essay for the FQXi contest in 2008, I explored what this feature of time means. Imagine slicing up spacetime from past to future; each slice is the 3-D totality of space at one instant of time. The sum of all these slices of spacelike-related events is 4-D spacetime. Alternatively, imagine looking at the world sideways and slicing it up accordingly. From this perspective, each 3-D slice is a strange amalgam of events that are spacelike-related (in just two dimensions) and timelike-related. These two methods of slicing are like carving up a loaf of bread either vertically or horizontally [*see box on preceding page*].

The first method is familiar to physicists, not to mention moviegoers. The frames of a movie represent slices of spacetime: they show space at successive moments of time. Like film aficionados who instantly figure out the plot and predict what happens next, physicists can take a single complete spatial slice and reconstruct what happens on the other spatial slices, simply by applying the laws of physics.

CAUSAL SETS

Defenders of Time's Flow

Not all physicists think the world is fundamentally timeless. One of the more intriguing alternative ideas is causal set theory, developed by Rafael Sorkin and David Rideout of the Perimeter Institute for Theoretical Physics in Ontario. It supposes that the world is a set of events, called a causet, which grows as new events come into existence according to probabilistic rules. The hope is that the process reproduces the features of spacetime that we perceive, including the flow of time. An outstanding question, though, is whether this process produces worlds that are compatible with relativity theory. —C.C.

The second method of slicing has no simple analogy. It corresponds to carving up spacetime not from past to future but from east to west. An example of such a slice might be the north wall in your house plus what will happen on that wall in the future. From this slice, you apply the laws of physics to reconstruct what the rest of your house (and indeed the rest of the universe) looks like. If that sounds strange, it should. It is not immediately obvious whether the laws of physics let you do that. But as mathematician Walter Craig of McMaster University and philosopher Steven Weinstein of the University of Waterloo have shown, you can, at least in some simple situations.

Although both methods of slicing are possible in principle, they are profoundly different. In the normal, past-to-future slicing, the data you need to collect on a slice are fairly easy to obtain. For instance, you measure the velocities of all particles. The velocity of a particle in one location is independent of the velocity of a particle someplace else, making both of them straightforward to measure. But in the second method, the particles' properties are not independent; they have to be set up in a very specific way, or else a single slice would not suffice to reconstruct all the others. You would have to perform extremely difficult measurements on groups of particles to gather the data you need. To make matters worse, only in special cases, such as the one Craig and Weinstein discovered, would even these measurements allow you to reconstruct the full spacetime.

In a very precise sense, time is the direction within spacetime in which good prediction is possible—the direction in which we can tell the most informative stories. The narrative of the universe does not unfold in space. It unfolds in time.

QUANTUM TIME

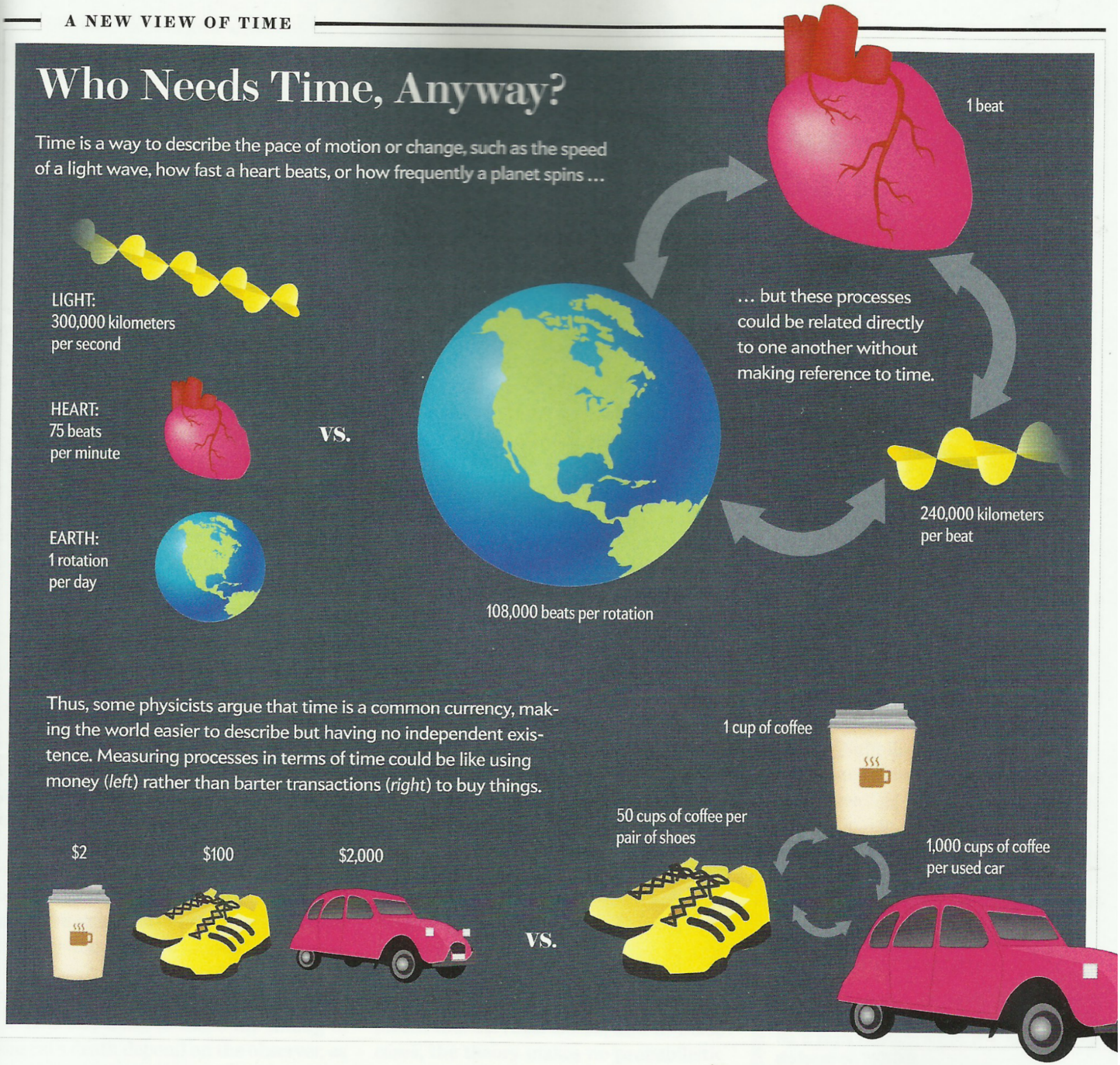
ONE OF THE HIGHEST GOALS of modern physics is to unite general relativity with quantum mechanics, producing a single theory that handles both the gravitational and quantum aspects of matter—a quantum theory of gravity. One of the stumbling blocks has been that quantum mechanics requires time to have properties that contradict what I have said so far.

Quantum mechanics says that objects have a much richer repertoire of behaviors than we can possibly capture with classical quantities such as position and velocity. The full description of an object is given by a mathematical function called the quantum state. This state evolves continuously in time. Using it, physicists are able to calculate the probabilities of any experimental outcome at any time. If we send an electron through a device that will deflect it either up or down, quantum mechanics may not be able to tell us with certainty which outcome to expect. Instead the quantum state may give us only probabilities of outcomes; for instance, a 25 percent chance the electron will veer upward and a 75 percent chance it will veer downward. Two systems described with identical quantum states may give different outcomes. The outcomes of experiments are probabilistic.

The theory's probabilistic predictions require time to have certain features. First, time is that which makes contradictions possible. A rolled die cannot have both 5 and 3 facing up at the same time. It can do so only at different times. Connected to this feature is the fact that the probability of landing on each of the six numbers must add up to 100 percent, or else the concept of probability would not be meaningful. The probabilities add up at a time, not at a place. The same is true of the probabilities for quantum particles to have a given position or momentum.

Second, the temporal order of quantum measurements makes a difference. Suppose I pass an electron through a device that deflects it first along the vertical direction, then along the horizontal direction. As it emerges, I measure its angular momentum. I repeat the experiment, this time deflecting the electron horizontally, then vertically, and measuring its angular momentum again. The values I get will be vastly different.

Third, a quantum state provides probabilities for all of space at an instant of time. If the state encompasses a pair of particles, then measuring one particle instantaneously affects the other no matter



Who Needs Time, Anyway?

Time is a way to describe the pace of motion or change, such as the speed of a light wave, how fast a heart beats, or how frequently a planet spins …

… but these processes could be related directly to one another without making reference to time.

Thus, some physicists argue that time is a common currency, making the world easier to describe but having no independent existence. Measuring processes in terms of time could be like using money (*left*) rather than barter transactions (*right*) to buy things.

LIGHT:
300,000 kilometers per second
HEART:
75 beats per minute
EARTH:
1 rotation per day
VS.
1 beat
240,000 kilometers per beat
108,000 beats per rotation
$2
$100
$2,000
VS.
1 cup of coffee
50 cups of coffee per pair of shoes
1,000 cups of coffee per used car

where it is—leading to the infamous "spooky action at a distance" that so troubled Einstein about quantum mechanics. The reason it bothered him was that for the particles to react at the same time, the universe must have a master clock, which relativity expressly forbids.

Although some of these issues are controversial, time in quantum mechanics is basically a throwback to time in Newtonian mechanics. Physicists fret about the absence of time in relativity, but perhaps a worse problem is the central role of time in quantum mechanics. It is the deep reason that unification has been so hard.

WHERE DID THE TIME GO?

A LARGE NUMBER of research programs have sought to reconcile general relativity and quantum mechanics: superstring theory, causal triangulation theory, noncommutative geometry, and more. They split roughly into two groups. Physicists who think quantum mechanics provides the firmer foundation, like superstring theorists, start with a full-blooded time. Those who believe that general relativity provides the better starting point begin with a theory in which time is already demoted and hence are more open to the idea of a timeless reality.

To be sure, the distinction between these two approaches is blurry. Superstring theorists have investigated timeless theories. To convey the basic problem that time poses, I will focus on the second approach. The leading instance of this strategy is loop quantum gravity [see "Atoms of Space and Time," by Lee Smolin, on page 94], which descends from an earlier program known as canonical quantum gravity.

Canonical quantum gravity emerged in the 1950s and 1960s, when physicists rewrote Einstein's equations for gravity in the same form as the equations for electromagnetism, the idea being that the same techniques used to develop a quan-

This vast network of correlations is neatly organized so that we can define something called "time" and relate everything to it, relieving ourselves of the burden of keeping track of all those direct relations. Physicists are able to compactly summarize the workings of the universe in terms of physical laws that play out in time. Yet this convenient fact should not trick us into thinking that time is a fundamental part of the world's furniture. Money, too, makes life much easier than negotiating a barter transaction every time you want to buy coffee, although it is an invented placeholder for the things we value, not something we value in and of itself. Similarly, time allows us to relate physical systems to one another without trying to figure out exactly how a glacier relates to a baseball. But it, too, may be a convenient fiction that no more exists fundamentally in the natural world than money does.

Getting rid of time has its appeal but inflicts a good deal of collateral damage. For one, it requires quantum mechanics to be thoroughly rethought. Consider the famous case of Schrödinger's cat. The cat is suspended between life and death, its fate hinging on the state of a quantum particle. In the usual way of thinking, the cat becomes one or the other after a measurement or some equivalent process takes place. Rovelli, though, would argue that the status of the cat is never resolved. The poor thing may be dead with respect to itself, alive relative to a human in the room, dead relative to a second human outside the room, and so on.

It is one thing to make the timing of the cat's death depend on the observer, as special relativity does. It is rather more surprising to make whether it even happens relative, as Rovelli suggests, following the spirit of relativity as far as it will go. Because time is so basic, banishing it would transform physicists' worldview.

THE RECOVERY OF TIME

EVEN IF THE WORLD is fundamentally timeless, still it seems as though it does have time in it. An urgent question for anyone espousing timeless quantum gravity is explaining why the world seems temporal. General relativity, too, lacks Newtonian time, but at least it has various partial substitutes that together behave like Newtonian time when gravity is weak and relative velocities low. The Wheeler-DeWitt equation lacks even those substitutes. Barbour and Rovelli have each offered suggestions for how time (or at least the illusion of time) could pop out of nothingness. But canonical quantum gravity already offers a more developed idea.

Known as semiclassical time, it goes back to a 1931 paper by English physicist Nevill F. Mott that described the collision between a helium nucleus and a larger atom. To model the total system, Mott applied an equation that lacks time and usually is applied only to static systems. He then divided the system into two subsystems and used the helium nucleus as a "clock" for the atom. Remarkably, the atom, relative to the nucleus, obeys the standard time-dependent equation of quantum mechanics. A function of space plays the role of time. So even though the system as a whole is timeless, the individual pieces are not. Hidden in the timeless equation for the total system is a time for the subsystem.

Much the same works for quantum gravity, as Claus Kiefer of the University of Cologne in Germany, following in the footsteps of Thomas Banks of the University of California, Santa Cruz, and others, argued in his FQXi essay. The universe may be timeless, but if you imagine breaking it into pieces, some of the pieces can serve as clocks for the others. Time emerges from timelessness. We perceive time because we are, by our very nature, one of those pieces.

As interesting and startling as this idea is, it leaves us wanting more. The universe cannot always be broken up into pieces that serve as clocks, and in those cases, the theory makes no probabilistic predictions. Handling those situations will take a full quantum theory of gravity and a deeper rethinking of time.

Historically, physicists began with the highly structured time of experience, the time of a fixed past, a present and an open future. They gradually dismantled this structure, and little, if any, of it remains. Researchers must now reverse this train of thought and reconstruct the time of experience from the time of nonfundamental physics, which itself may need to be reconstructed from a network of correlations among pieces of a fundamental static world.

French philosopher Maurice Merleau-Ponty argued that time itself does not really flow and that its apparent flow is a product of our "surreptitiously putting into the river a witness of its course." That is, the tendency to believe time flows is a result of forgetting to put ourselves and our connections to the world into the picture. Merleau-Ponty was speaking of our subjective experience of time, and until recently no one ever guessed that objective time might itself be explained as a result of those connections. Time may exist only by breaking the world into subsystems and looking at what ties them together. In this picture, physical time emerges by virtue of our thinking ourselves as separate from everything else.

TIME MAY EXIST ONLY BY BREAKING THE WORLD INTO SUBSYSTEMS AND LOOKING AT WHAT TIES THEM TOGETHER.

MORE TO EXPLORE

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